The second explanation is that some form of refraction or multipath propagation through the Jovian atmosphere is occurring, which is introducing errors into the radio propagation results. The occultation experimenters are presently investigating the validity of this second explanation.

The imaging photopolarimeter has taken pictures of the planet, both from equatorial and high latitude locations. The Pioneer 11 images are the first polar images of Jupiter ever recorded. They show a decrease in the banding structure of the planet with increased latitude and a more mottled structure across the poles.

Postencounter. Pioneer 11 passed Jupiter on a retrograde encounter trajectory. After encounter the spacecraft swung onto a path to intercept Saturn in September 1979. At the present time all instruments are functioning properly, and they give every indication of surviving until the Saturn encounter.

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17 March 1975

Pioneer 11 Encounter: Preliminary Results from the Ames Research Center Plasma Analyzer Experiment

Abstract. *Pioneer 11 observations of the interaction of Jupiter's magnetosphere with the distant solar wind have confirmed the earlier Pioneer 10 observations of the great size and extreme variability of the outer magnetosphere. The nature of the plasma transitions across Jupiter's bow shock and magnetopause as observed on Pioneer 10 have also been confirmed on Pioneer 11. However, the northward direction of the Pioneer 11 outbound trajectory and the distance of the final magnetopause crossing (80 Jupiter radii) now suggest that Jupiter's magnetosphere is extremely broad with a half-thickness (normal to the ecliptic plane in the noon meridian) which is comparable to or greater than the sunward distance to the nose.*

The Pioneer 11 spacecraft, launched on 6 April 1973, passed by Jupiter at a distance of 113,850 km from the center of the planet at 0522 on 3 December 1974. (The times in this report are U.T. and refer to the spacecraft location.) As in the case of Pioneer 10, which a year earlier was the first spacecraft to explore the Jovian environment (*1*), the Pioneer 11 payload included a plasma analyzer experiment to measure properties of the interplanetary plasma (solar wind) from Earth's orbit to beyond the orbit of Jupiter, as well as the interaction with Jupiter's magnetosphere. The Pioneer 11 Ames Research Center plasma analyzer experiment is identical to that on Pioneer 10 and uses two separate quadrispherical 90° electrostatic analyzers for energy and angular analysis (*2, 3*). A medium-resolution analyzer uses five separate current collectors with associated electrometer tube amplifiers as detectors; a high-resolution analyzer uses 26 Bendix Channeltron electron multipliers as detectors. Both the Pioneer 10 and the Pioneer 11 spacecrafts are spin-stabilized, with the spin axis oriented so that the spacecraft high-gain communications antenna is directed earthward. The entrance apertures for both electrostatic analyzers in the plasma experiment are directed along the spacecraft spin axis. Consequently the spacecraft spin, or roll (5.0 rev min^{-1} during Pioneer 11 encounter), makes possible plasma flux measurements at various azimuthal angles of the spacecraft spin, whereas the multiple detectors just described make possible, at any spacecraft roll angle, plasma flux measurements at various polar angles with respect to the spacecraft spin axis. The complete experiment covers a proton energy range of 100 to 18,000 ev and an electron energy range of approximately 1 to 500 ev.

Pioneer 11 approached Jupiter in the morning quadrant at an angle with respect to the solar direction slightly greater than 40°, similar to the case of Pioneer 10. The encounter trajectory of Pioneer 11 is given in Fig. 1, both projected onto Jupiter's equatorial plane and as an orthogonal projection on a plane that contains the direction to the Sun. As seen in Fig. 1, the Pioneer 11 outbound trajectory, which permits encounter with the planet Saturn in early September 1979, was toward the solar direction and northward.

As in the case of Pioneer 10 (*3*), bow stock and magnetopause boundaries were identified in the Pioneer 11 plasma experiment data during Jupiter encounter, forming an analogy with the case of Earth's interaction with the solar wind (*4*). The bow shock, at which the flow Mach number drops below unity, is a standing discontinuity in the solar wind upstream from the magnetopause. The magnetopause forms the boundary between the shocked solar plasma (magnetosheath) and the planetary magnetic field (magnetosphere) around which the solar wind plasma is deflected. The multiple observations of Jupiter's bow shock and magnetopause are accounted for as a result of motion of these surfaces toward and away from Jupiter, past the spacecraft, in response to changing solar wind dynamic pressure.

The inward bow shock crossings are signaled by an abrupt decrease in the solar wind bulk speed accompanied by a flow deflection on the order of 30° or more, a proton number density increase, and a large proton temperature increase. The first Pioneer 11 Jupiter bow shock crossing was observed at 0339 on 26 November 1974 at a planet-centered distance of 109.7 R_J (R_J = Jupiter radius, taken to be 71,372 km). At this time the solar wind bulk speed (spacecraft frame of reference) decreased from 480 to 328 km sec^{-1} with a concurrent shift of the flow direction of approximately 50° and a proton isotropic temperature increase from about 2×10^4 to 5×10^5 K. The transition time for the proton bulk speed is longer than 10 minutes in this case. The time for proton bulk speed changes at these shock crossings generally seems to be longer than the times for the flow direction and temperature changes. The proton number density increased by at least a factor of 2.5 across the shock transition from an upstream value of 0.06 cm^{-3}. More precise values of the density jump across the inbound shock crossings are not yet available in the preliminary data because correction factors still have to be applied to account for the large plasma flow angle (40° to 50°) with respect to the spacecraft spin axis in the magnetosheath.

Preliminary plasma parameters obtained during the early part of the Pioneer 11 inbound trajectory are given in Fig. 2. The upstream values are calculated from linear least-squares fits to the currents of the medium-resolution detector. Magnetosheath parameters are estimated from velocity distribution moments calculated from counts of one of the outermost two channel multipliers of the high-resolution detector. Each of these two multipliers views at an angle of 50° away from the spacecraft spin axis and has a larger geometric factor than the remaining multipliers. The Pioneer 11 magnetosheath plasma flow directions examined to the time of writing all are closer to the spacecraft spin axis than 50°, except that the plasma flux sometimes is too low to permit a determination of the flow direction. Some data gaps in Fig. 2 are at times

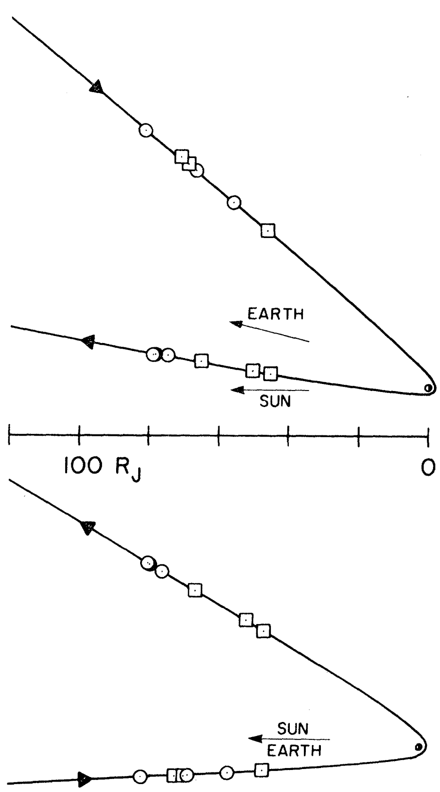


Fig. 1. Pioneer 11 trajectory during encounter with Jupiter. The upper graph gives a projection on Jupiter's equatorial plane, viewed from the north. The lower graph gives an orthogonal projection on a plane that contains the Jupiter-Sun direction. Locations of bow shock and magnetopause crossings identified in data from the Ames Research Center plasma analyzer experiment are given as circles and squares, respectively.

of specialized instrument modes during which plasma parameters have not yet been calculated. Other small gaps in these plots correspond to gaps in the preliminary data tapes used for this analysis.

The inward magnetopause crossings are identified by the disappearance of detectable flowing plasma. The first such crossing observed on Pioneer 11 was at ~ 0245 on 27 November 1974, at 97.3 R_J. From 0241 to 0245 the high-resolution analyzer detected plasma ions in the 260- to 2800-ev energy steps, at levels above a background due to penetrating magnetospheric energetic electrons by a factor of 2. Before this time the plasma ions were detected at even higher levels above background. After this time no plasma was detected for several hours above the background. After the magnetopause crossing the background remained constant for more than 15 minutes and then began an hour-long rise to a peak. For energies from 1500 to 1700 ev there was an exception to this pattern since fluxes reappeared above background by a factor of 2 for about 15 seconds at 0250 (plasma burst) on the energy cycle that followed the one described above.

The locations of bow shock and magnetopause crossings identified from the data obtained during the Pioneer 11 encounter with Jupiter are given in Fig. 1. Table 1 gives the times and distances from the center of Jupiter of these observations.

The relatively large uncertainty in the time for the second magnetopause crossing on the inbound trajectory is due to difficulty with the preliminary data tape for this time period. It is not thought likely that further magnetosheath boundaries will be identified in this data, although, as of the time of writing, about 30 percent of the approximately 72 hours of magnetosheath data remains unexamined.

The fact that on its outbound trajectory Pioneer 11 remained within Jupiter's magnetosphere, except for somewhat less than 10½ hours on 6 December, until 80 R_J from Jupiter (~ 30° northward from the nose) is evidence for a fairly thick magnetosphere. Specifically, if twice the distance from Jupiter's equatorial plane is used as a limit to a magnetospheric radius, then this lower limit is 82 R_J, comparable in scale with the more distant magnetopause crossings observed on the inbound trajectories of both Pioneer 10 and Pioneer 11 at 96 and 97 R_J, respectively.

This lower limit is calculated on the assumption of a model ("fedora hat") for Jupiter's magnetosphere that contains a disklike current sheet parallel to Jupiter's equatorial plane as proposed by Smith *et al.* (*5*). The origin of this current sheet in Jupiter's planetary magnetic field is tilted with respect to the equator, so the distant portions of the sheet at a given longitude move up and down during the planet's rotation. If, on the other hand, this model is not correct and Jupiter's distant magnetosphere rotates like a rigid dipole, the lower limit magnetospheric half-thickness is on the order of 55 R_J, measured to the estimated point of highest magnetic latitude reached by Pioneer 11 before final exit from Jupiter's magnetosphere.

The wide range of distances over which Pioneer 11 encountered Jupiter's magnetosphere, differing by 50 percent on the inbound trajectory and by 40 percent on the outbound trajectory, confirms the similar earlier Pioneer 10 observations of a highly variable, "spongy" outer magnetosphere.

The data of Table 1 indicate that

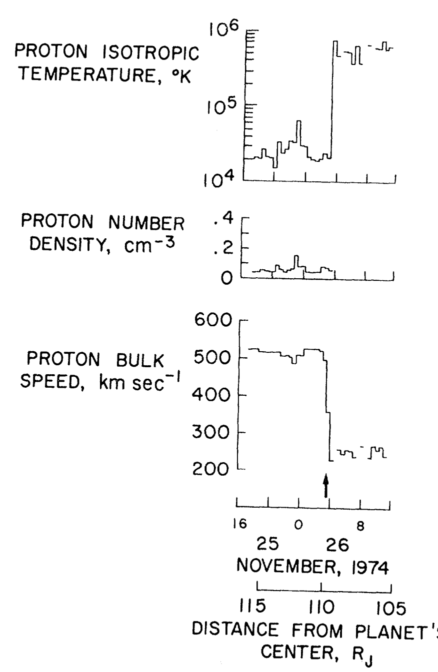
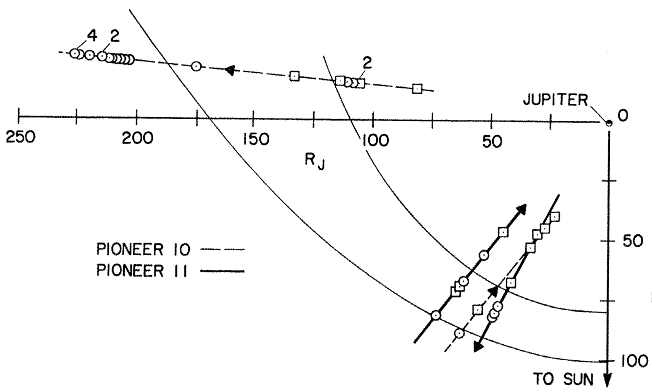


Fig. 2. Preliminary half-hour averages of proton bulk speed, number density, and isotropic temperature measured on the inbound trajectory. The time of the first bow shock crossing is indicated by a solid arrow. The spacecraft velocity has not been removed from the speed measurements.



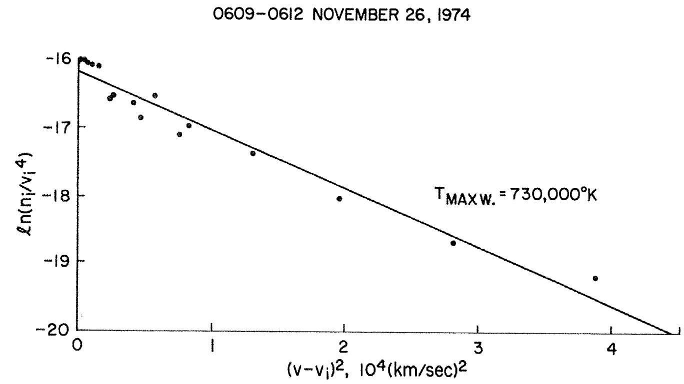


Fig. 3 (left). Pioneer 11 and Pioneer 10 bow shock and magnetopause crossing locations rotated onto a common plane parallel to the ecliptic and viewed from the north. Circles represent bow shock observations, and squares represent magnetopause crossings. A pair of curved light lines give bow shock and magnetopause shapes based on the gas dynamic analogy at Earth. Fig. 4 (right). Pioneer 11 high-resolution plasma analyzer energy distribution from Jupiter's magnetosheath taken at 108.4 R_J on the inbound trajectory. The straight line fit of the data indicates the Maxwellian character of the energy distribution.

the distances of the two most distant shock crossings and the two closest magnetopause crossings for the inbound and outbound trajectories are not too different, but the outbound distances are somewhat smaller. These relations would also suggest a forward magnetosphere shape for Jupiter somewhat less thick toward the poles than toward the nose. The most reliable empirical shape, in the gas dynamic analogy, for Jupiter's magnetopause could only be determined, with just a few boundary locations available, if the free-stream conditions are known at the times the magnetopause is crossed, and this dynamic information is not available from measurements by a single spacecraft.

A comparison of the Pioneer 11 and Pioneer 10 magnetosheath boundary locations is shown in Fig. 3, for which both sets of data are rotated into a common plane parallel to the ecliptic. It is a remarkable coincidence that the first inbound bow shock and magnetopause crossings detected by Pioneer 11 are less than 1 percent more distant from the planet than the corresponding Pioneer 10 crossings. The bow shock and magnetopause shapes based on the gas dynamic analogy at Earth suggest a wider magnetosheath than the Pioneer 11 and Pioneer 10 observations. If this suggestion is correct and not the effect of outward motion of these boundaries at the times of observation, it could be due to a higher free-stream Mach number or a different magnetosphere shape than the case at Earth.

The free-stream plasma measurements give comparable solar wind dynamic pressures upstream from the outermost bow shock crossings on both the Pioneer 11 inbound and outbound trajectories. When Jupiter's magnetosphere is compressed least by the free-stream solar wind pressure, it may tend to be more extended near the equatorial plane since, as mentioned above, the outermost bow shock and magnetopause crossing locations on the Pioneer 11 outbound trajectory are closer to Jupiter than the corresponding outermost locations of the Pioneer 11 and Pioneer 10 inbound trajectories. For the Pioneer 11 inbound trajectory, the innermost bow shock crossing is preceded by solar wind dynamic pressure values larger by about a factor of 4 than those before the outermost shock crossing. This observation is consistent with compression of the magnetosphere by the solar wind so that the bow shock and magnetopause are then closer to the planet.

Some analysis has been done of details of the plasma energy spectra measured within Jupiter's magnetosheath. If samples of a convecting velocity distribution function are plotted on a logarithmic scale against the square of the sample velocity difference from the bulk velocity $\vec{V}$, the data points will fall on a straight line if the velocity distribution is Maxwellian. Figure 4 gives such a plot for data from the Pioneer 11 Ames Research Center high-resolution plasma analyzer from Jupiter's outer magnetosheath, taken 2½ hours after the first bow shock crossing observed on the inbound trajectory. Here the number of counts n_i in one of the outermost channel multipliers at energy step i divided by v_i^4 (where v_i is the proton speed for the corresponding energy step) is a measure of the speed distribution. The bulk velocity magnitude is taken as

$$|\vec{V}| \sim \frac{\Sigma\ (n_i/v_i^3)}{\Sigma\ (n_i/v_i^4)} = 239.5 \text{ km sec}^{-1}$$

Table 1. Magnetosheath boundaries observed by the Pioneer 11 Ames Research Center plasma analyzer experiment; S, shock; M, magnetopause.

Date (1974)	Time (U.T.)	Type of boundary	Distance (R_J)
	Inbound		
26 November	0339.3 ± 0.9	S	109.7
27 November	0246 ± 2.	M	97.3
27 November	0752 ± 26.	M	94.5 ± 0.2
27 November	1306.1 ± 0.1	S	91.6
28 November	1435.5 ± 0.3	S	77.5
29 November	1318.7 ± 0.8	M	64.5
	Outbound		
6 December	0806.5 ± 1.0	M	56.6
6 December	1828. ± 2.8	M	62.7
8 December	0036. ± 3.5	M	80.0
8 December	2014.5 ± 0.8	S	90.8
9 December	0256.3 ± 1.2	S	94.5
9 December	0346.0 ± 0.1	S	95.0

As can be seen in Fig. 4, the data points fall close to a straight line, indicating Maxwellian thermal characteristics. An unweighted least-squares straight line fit to the data points is also given in Fig. 4. Under the assumption that the velocity distribution is Maxwellian, the proton temperature in terms of the slope b of the straight line fit is

$$T_{\text{Maxw.}} = \frac{m}{2kb} = 730{,}000 \text{ K}$$

where m is the proton mass and k is Boltzmann's constant. Many of the Pioneer 11 proton speed distributions for the Jupiter magnetosheath (and those from Pioneer 10) have these Maxwellian characteristics.

In summary, the preliminary Pioneer 11 observations from the Ames Research Center plasma analyzer experiment provide a direct measurement that suggests that the half-thickness of Jupiter's magnetosphere is, at a minimum, comparable to the sunward distance to the nose. Pioneer 10 results for the size and variability of Jupiter's outer magnetosphere, and the nature of Jupiter's magnetopause and bow shock plasma transitions in the sunward direction, have been confirmed.

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6. We thank the Pioneer Project Office at Ames Research Center for their excellent effort and support during the Pioneer 11 mission. We also thank the TRW Systems group for construction of the spacecraft, and the Time-Zero Corporation, Torrance, California, for construction of the Ames Research Center plasma analyzer experiment.

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Jupiter's Magnetic Field, Magnetosphere, and Interaction with the Solar Wind: Pioneer 11

Abstract. *The Pioneer 11 vector helium magnetometer provided precise, continuous measurements of the magnetic fields in interplanetary space, inside Jupiter's magnetosphere, and in the near vicinity of Jupiter. As with the Pioneer 10 data, evidence was seen of the dynamic interaction of Jupiter with the solar wind which leads to a variety of phenomena (bow shock, upstream waves, nonlinear magnetosheath impulses) and to changes in the dimension of the dayside magnetosphere by as much as a factor of 2. The magnetosphere clearly appears to be blunt, not disk-shaped, with a well-defined outer boundary. In the outer magnetosphere, the magnetic field is irregular but exhibits a persistent southward component indicative of a closed magnetosphere. The data contain the first clear evidence in the dayside magnetosphere of the current sheet, apparently associated with centrifugal forces, that was a dominant feature of the outbound Pioneer 10 data. A modest westward spiraling of the field was again evident inbound but not outbound at higher latitudes and nearer the Sun-Jupiter direction. Measurements near periapsis, which were nearer the planet and provide better latitude and longitude coverage than Pioneer 10, have revealed a 5 percent discrepancy with the Pioneer 10 offset dipole model (D_2). A revised offset dipole (6-parameter fit) is presented as well as the results of a spherical harmonic analysis (23 parameters) consisting of an interior dipole, quadrupole, and octopole and an external dipole and quadrupole. The dipole moment and the composite field appear moderately larger than inferred from Pioneer 10. Maximum surface fields of 14 and 11 gauss in the northern and southern hemispheres are inferred. Jupiter's planetary field is found to be slightly more irregular than that of Earth.*

The results presented here are based on field vectors averaged over successive 5-minute intervals which were provided by the Pioneer Project in near real time (quick-look data). They were obtained with the vector helium magnetometer which is essentially identical to the Pioneer 10 instrument (*1*). As before, the magnetometer operated faultlessly and there were no anomalies of any kind associated with either the trapped radiation environment or other causes.

The magnetometer measures field components between 0.01 γ (10^{-5} gauss) and 1.4 gauss by automatically selecting one of eight ranges, all of which are linear to within 0.01 percent. On its highest range, the magnetometer is capable of measuring components at least as large as 1.35 gauss with an uncertainty of only ± 265 γ. Since the largest measured total field strength was significantly smaller (1.135 gauss), the dynamic range of the instrument was never exceeded. The prelaunch magnetometer calibrations were checked inflight at least once every month during the transit to Jupiter without significant changes being observed, so that the measurements are known to be accurate to within 1 percent. The magnetometer sensor is located at the end of a 5-m boom outside the influence of permanent, induced, or current-associated spacecraft magnetic fields. Vector measurements were obtained continuously throughout the encounter, including Earth occultation during which several hundred triaxial samples were stored in an on-board memory.

The effect of Jupiter on the solar wind observed farthest from the planet, as on Pioneer 10 (*2*), was the presence of hydromagnetic waves upstream of the Jovian bow shock. These waves were again associated with bursts of relativistic electrons escaping from Jupiter's magnetosphere detected simultaneously by the cosmic ray experiments (*3*). Six crossings of the Jovian bow shock were observed: three inbound (Fig. 1) at 110, 92, and 78 Jupiter radii (R_J), at $\simeq$ 0900 local time (L.T.) and a Jovigraphic latitude of $\simeq 7°$, and three outbound (Fig. 2) at 91, 94.5, and 95 R_J at 1130 L.T. and at a latitude of $\simeq 32°$. The shocks were typically perpendicular (flow perpendicular to the field) rather than parallel (or "pulsating"). The velocity of the moving bow shock in Jupiter's reference frame was estimated from the conservation of magnetic flux across a perpendicular shock,

$$V = \frac{(B_2V_2 - B_1V_1)}{(B_2 - B_1)}$$

where B is the field strength and V is the solar wind speed; the subscript "2"